Arthur D Little

Assessment of Planar Solid Oxide Fuel Cell Technology

Report to:
DOE FETC

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Arthur D. Little, Inc.
Acorn Park
Cambridge, Massachusetts
02140-2390

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In support of the 21st Century Fuel Cell Concept Team, we have assessed planar architectures for SOFC technology.

Tasks

- Literature Review of Planar SOFC Programs
- Interviews with Major Developers
- Assess Status of Planar SOFC Technology
  - Technology
  - Cost

We report the results of this study in the following presentation-style document.

Since 1997, when Arthur D. Little last assessed planar SOFC technology, advances in design and engineering have significantly improved the technical and commercial viability of planar SOFC architectures.

- Developers have shifted from all-ceramic high temperature (1000°C) designs to metal interconnect (IC) intermediate temperature (650–800°C) designs.
  - Designs are based on anode supported unit cells with thin (5–50 µm) electrolytes
    - all ceramic designs used electrolyte thicknesses of 150–200µm.
  - Use of ferritic stainless steel (typically with a coating) is now possible at lower operating temperatures.
    - coating stabilizes and protects surface, and lowers contact resistance.
  - Potential for significantly higher power densities claimed (≥ 500 mW/cm^2).
  - Developers indicate that lower temperatures and the shift to anode supported metal IC designs have aided the development of viable seal designs.
- Metal IC low temperature designs have been demonstrated in unit cells and short stacks (e.g., 2–10 cells) with small electrodes (e.g., 100 cm^2).
  - Developers are using established electrochemical materials from all-ceramic designs to demonstrate metal IC designs.
    - structure of electrodes (e.g., porosity) has been modified for higher power operation.
  - Benefits of more conductive experimental electrolytes will be realized as they become available.

The available information (literature and discussions with developers) suggest that fuel processing will be performed in a separate but thermally integrated reformer section, analogous to current tubular designs.

- Thermal management and control issues of combining the reforming and electrochemical reactions on the same surface remains a fundamental problem.
  - Endothermic reforming reactions lower temperatures, slowing the kinetics of the electrochemical processes.
  - Ability to control rate of reformer reactions relative to optimum local electrochemical demand for H_2.
  - Internal on electrode reforming reported, but at lower power levels.
- Manufacturing, mechanical, thermal, and performance limitations on scale of the unit cell area and stack voltage are not discussed in open literature.
  - Practical limitations (e.g., manufacturing, seal designs)
  - Theoretical limitations (e.g., thermal transport, diffusion)
  - Engineering and system trade-offs (power, efficiency, fuel utilization, and cost)

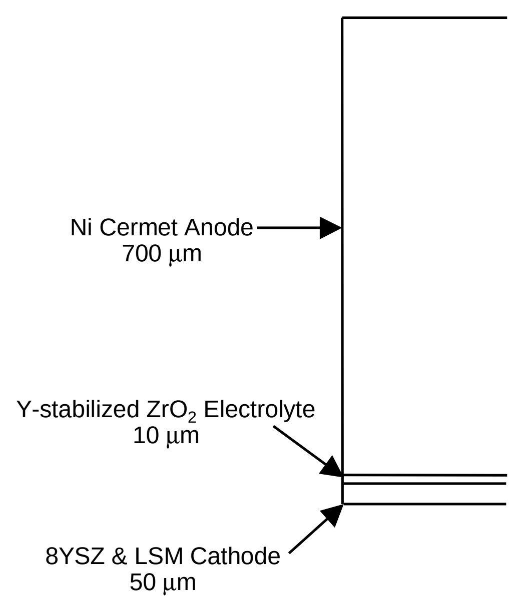
Based on current industry trends, a generic baseline planar design was selected with the following characteristics:

- An anode supported electrolyte having a thickness of 10 µm (assumed to be yttria stabilized zirconia, YSZ)
- Ferritic stainless steel separator plates with flow passages formed by conventional fabrication techniques
- Ferritic stainless steel manifolds
- A pitch of 5 cells per inch and an active cell area of 100 cm^2 (i.e. 10 cm square)
- Power densities ranging from 200 mW/cm^2 to 500 mW/cm^2
  - the higher end is claimed by developers to be readily achievable with the thinner electrolytes and reduced internal electrical resistances

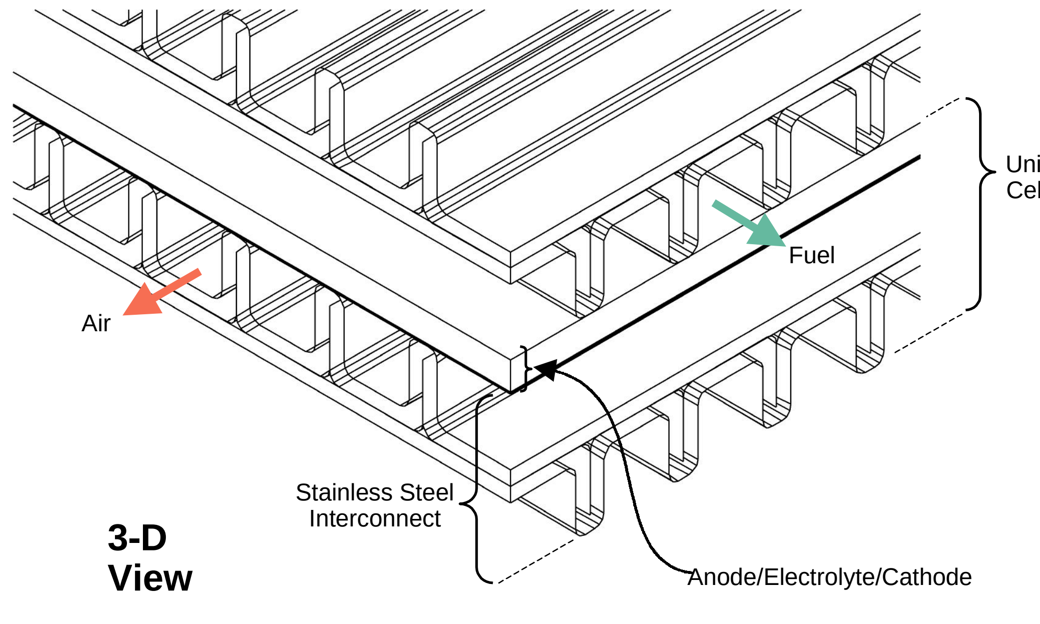
The generic design corresponds functionally with those being pursued by several developers relative to such key issues impacting costs such as materials utilization, fabrication techniques for the electrode/electrolyte structures, and performance.

We have used the planar unit cell configuration and materials shown below.

Anode Supported Unit Cell



Cross-Flow Stack Configuration



The design has a area of 100 cm² and a pitch of 5 unit cells per inch.

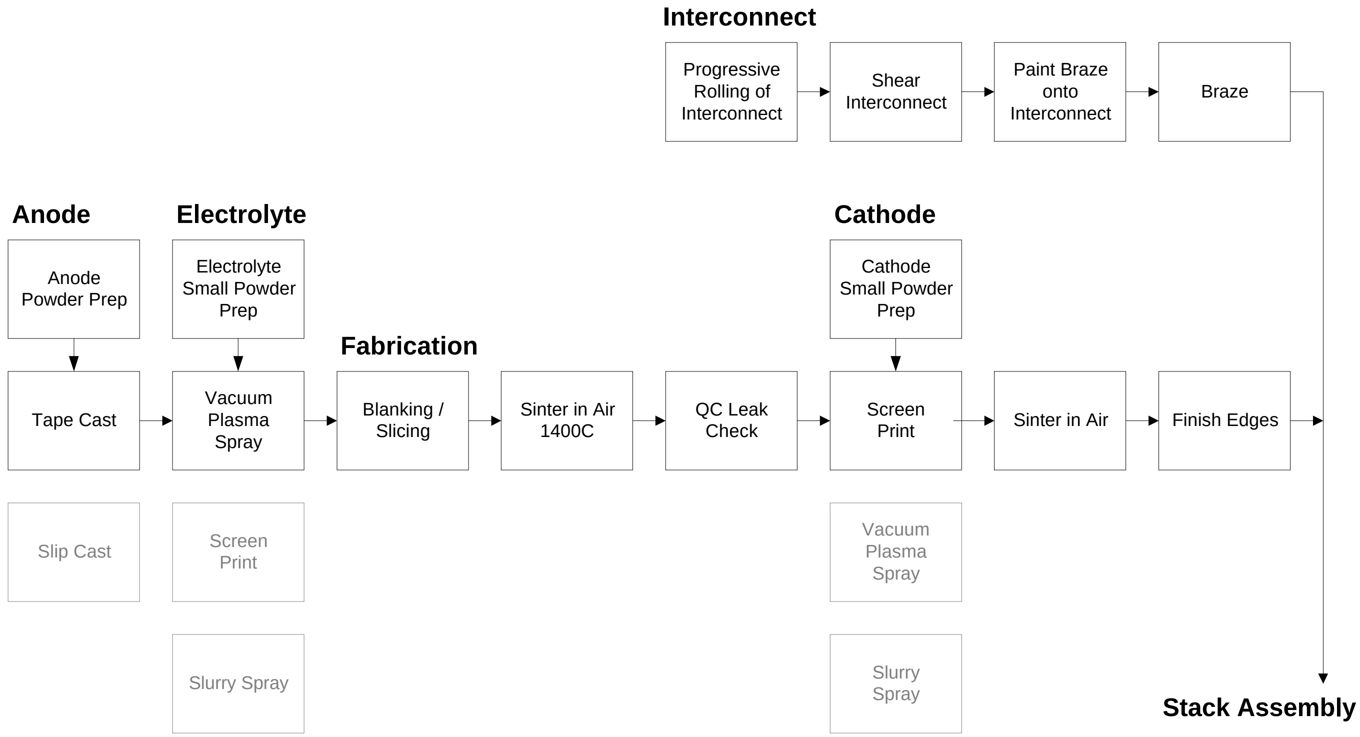
The design selected has comparable volumetric density to an all-ceramic design assessed in 1997, but higher gravimetric density.

		Anode Supported Electrolyte (1999) Metal Interconnect	**Electrolyte Supported Electrodes** (1997 METC Analysis*) Ceramic Interconnect
Electrochemical Layers	**Anode (µm)**	700	37
	Electrolyte (µm)	10	165
	Cathode (µm)	50	28
	Wt./area (g/cm^2)	0.36	0.13
	Vol./area (cm^3/cm^2)	0.08	0.02
Interconnect	**Interconnect (µm)**	4320	4850
	Wt./area (g/cm^2)	1.29	0.94
	Vol./area (cm^3/cm^2)	0.43	0.49
Total Unit Cell	**Wt./area (g/cm^2)**	1.65	0.94
	Vol./area (cm^3/cm^2)	0.51	0.51
	Pitch (cells per inch)	5	5
	Density (g/cm^3)	3.2	1.8

* METC reference 1997 Contract # 54427-05

The cost analysis of the low temperature metallic IC planar design is based on a process flow in which successive layers are individually fired.

Multi-Fired Process Flow



Note: Alternative production processes appear in gray to the bottom of actual production processes assumed

Process Flow Assumptions

- Electrical layer powders are made by ball milling and calcining.
- Interconnects are made by metal forming techniques.
- Automated inspection of the electrical layers occurs after sintering.

On an area/material basis, the metallic IC design is approximately 45% less expensive than the all ceramic construction. The cost reductions in electrolyte and interconnect materials and assembly of the Metal IC design outweigh the increased anode material cost.

	Planar Metal IC $\$/m^2$		Planar All-Ceramic* $\$/m^2$	
	Material	Process	Material	Process
Anode	$204.16	$8.52	$10.03	$3.86
Cathode	$4.52	$5.37	$3.43	$3.34
Electrolyte	$35.69	$18.04	$190.29	$15.63
Interconnect	$81.94	$15.27	$360.07	$31.15
Layer Assembly		$55.55		$135.61
Subtotal	$326	$103	$564	$190
Total	$429		$753	

*Updated 1997 METC estimate

The above costs do not include protective conductive coatings on the metallic interconnect, which if needed, could increase overall costs by 5-10%.

The increased power density and lower materials costs of the metallic interconnect planar SOFC designs make them significantly less costly than older all ceramic planar designs.

	Comparison of Stack Structure Cost				
SOFC Technology	**g/cm^2**	**\$/m^2**	**Power Density mW/cm^2**	**Power Density kW/kg**	**Cost (Materials and Processing) \$/kW**
Planar Metal IC (This Study)	1.7	\$429	500	.24	\$86
1997 Updated Planar All Ceramic	1.1	\$753	200	.38	\$377

The overall fuel cell stack module includes:

- Fuel cell stack structure
- Manifolds/reactant gas piping
- High temperature insulation
- Container vessel (assumed 3 atmosphere operation in integrated system designs)
- Reformer “boards” in thermal contact with the core stack structure

The “reformer boards” are not used in all system strategies which can include external reforming (i.e. outside the stack module structure) and on anode reforming (still experimental).

Higher power density, less expensive materials, and smaller volume of the metallic IC design lower the cost relative to earlier estimates for the all ceramic planar design.

	Reformer Type	Power Density (mW/cm^2)	Stack Structure ($/kw) • Cathode • Electrolyte • Anode • Inter-connect	Balance of Stack ($/kw) • Seals • Manifolds • Electrical Bus-bars • Pressure Vessel • Reformer • Support Structure	Fuel Cell Module Cost ($/kw)
1997 Updated Planar All-Ceramic	Separate Thermally Integrated	200	$377	$116	$493
1999 Planar SOFC with Metallic IC	Separate Thermally Integrated	500	$86	$80	$166

Balance of plant costs of approximately $600/kW were assumed for each each design to arrive at an overall system cost.

Balance of Plant
• Turbine/generator • Power conditioning • Grid interface • Controls • Piping and valves

	Power Density (mW/cm²)	"Integrated Cycle"	System Cost $/kw
1997 Planar All Ceramic	200	Yes*	$1090
1999 Planar Metallic IC	500	Yes*	$766

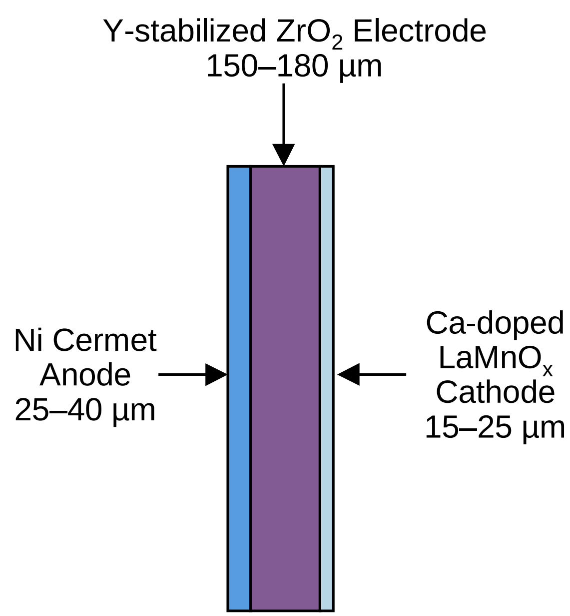
Arthur D. Little has conducted a succession of SOFC assessments over the years.

- Overview of fuel cell technologies for SOCAL (1990) with SOFC included
- Cost/Design/Manufacturing Assessments for Westinghouse - DOE
  - Planar versus Tubular SOFC analysis based on all ceramic electrolyte supported unit cell (1997)
    - electrode supported electrolyte designs mentioned
- FETC (1998) Review of Cobb Associates FETC Advanced SOFC Cost Analysis
- Siemens-Westinghouse (1999) Transfer of cost model to Siemens
- FETC (1999) Present Assignment

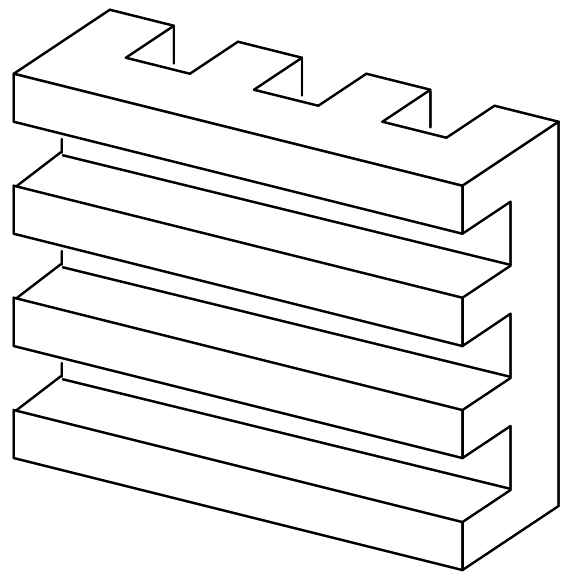
ADL has conducted the most recent FETC assignment within the context of the 21st Century Fuel Cell Concept Team.

In 1997, the analysis for METC considered an all ceramic design with electrolyte supported electrodes.

Unit Cell Cross-Section



Injection Molded Interconnect Plate



Ca-doped $LaCrO_3$ ceramic

Injection molding was selected for fabrication of the ceramic interconnects.

Our assessment has focused on recent technology advances leading to increased development activity in planar SOFCs.

Technology Developments		
Materials	**Design**	**System**
• Higher conductivity electrolytes • **Metallic interconnect plates**	• **Electrode supported thin electrolyte** unit cells – e.g., anode • Composite electrode design – Electrode/electrolyte mixture to enhance 3-phase region	• **Lower temperature** of operation • Stand-alone versus Integrated Cycle systems

The change to thin electrolyte layers has led to lower operating temperatures and the opportunity to use metallic interconnect plates.

The shift to thinner electrolyte layers has created the opportunity to lower operating temperature and to use metal interconnects, while still increasing power density.

	Technology Advance	Potential Benefit
Design	Electrode supported **thin electrolyte** unit cells	• Lower resistance of electrolyte • Increased power density
System	**Lower temperature** of operation	• Use of metallic interconnects and manifolding now possible
Materials	**Metallic Interconnect Plates**	• Lower Cost • Lower Resistance Interconnect • Mechanical Solution to Thermal Expansion of Stack

Development of higher conductivity electrolytes will further enhance these benefits.

Developers are first evaluating electrode (i.e., anode) supported electrolyte layers with yttria stabilized zirconia (YSZ), a proven material.

Electrolyte	Base Technology	Advances	Benefit
Material	Yttria Stabilized Zirconia (YSZ)	More conductive materials considered: • Sc-Zr Oxides • Ce-Gd based Oxides • Bi based Oxides	Reduced Voltage drop across electrolyte
Thickness	150–200 µm	Reduced thickness (5–50µm, 10-20 µm common)	

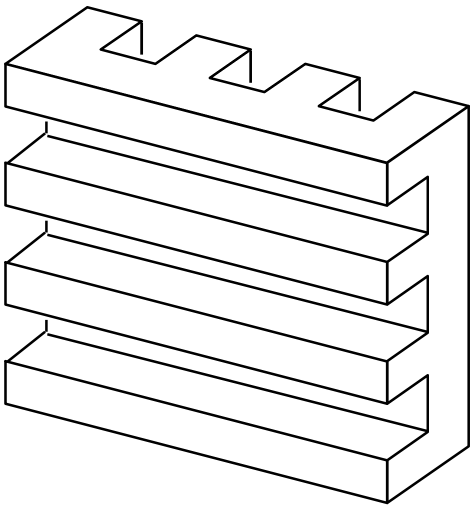
Higher conductivity electrolytes may allow use of thicker electrolyte layers at lower temperatures.

A "bipolar" interconnect plate serves several functions and must meet several requirements.

Functions

- Gas barrier between anode and cathode
- Electrical connector between anode and cathode (series)
- Flow field (distribution of fuel and oxidant)

Cross-Flow Bipolar Plate Configuration



Requirements

- Impermeability
- Mechanical
  - Strength
  - "Flexibility/Compliance"– compensate for differences in TEC, conformability
  - Flatness and dimensional tolerances
- Electrical
  - Bulk conductivity
  - Contact resistance
- Pressure Drop (flow field design)
- Manufacturability
- Material Stability
- Cost

Stability of protective metal oxides in stainless steels, e.g. Cr_2O_3, will depend on temperature and oxygen activity in the gas. Movement of chromium into the electrochemical layers will degrade performance.

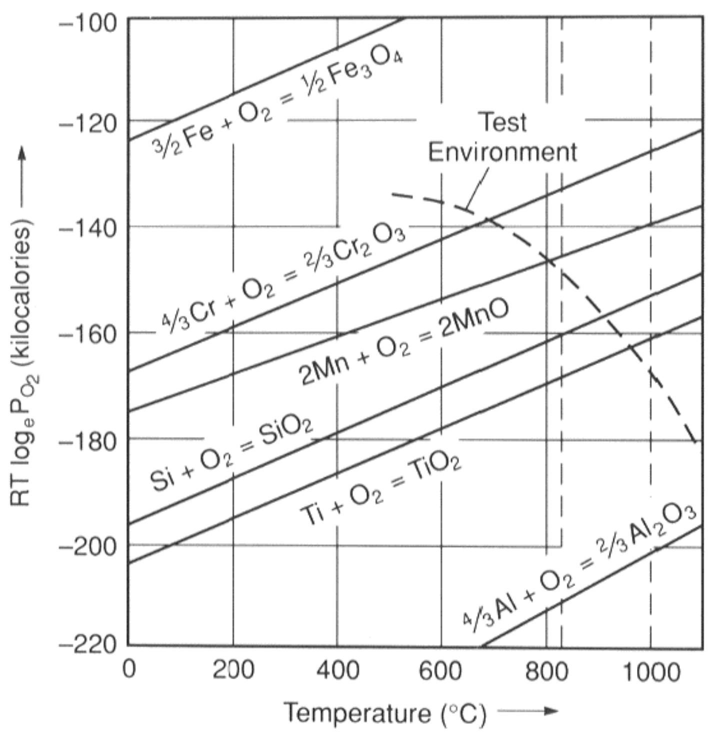


Fig. 4.12 Oxygen potential of the test environments used by Norton and his colleagues in carburization studies at Petten Laboratories. (Source: Ref 27-29)

(*G.Y. Lai, High-Temperature Corrosion of Engineering Alloys, ASM 1990)

Some developers are using coatings on the ferritic stainless steel IC's to protect the surface and prevent chromium contamination of the electrodes.

Metal interconnect plates are a critical element of the new SOFC designs.

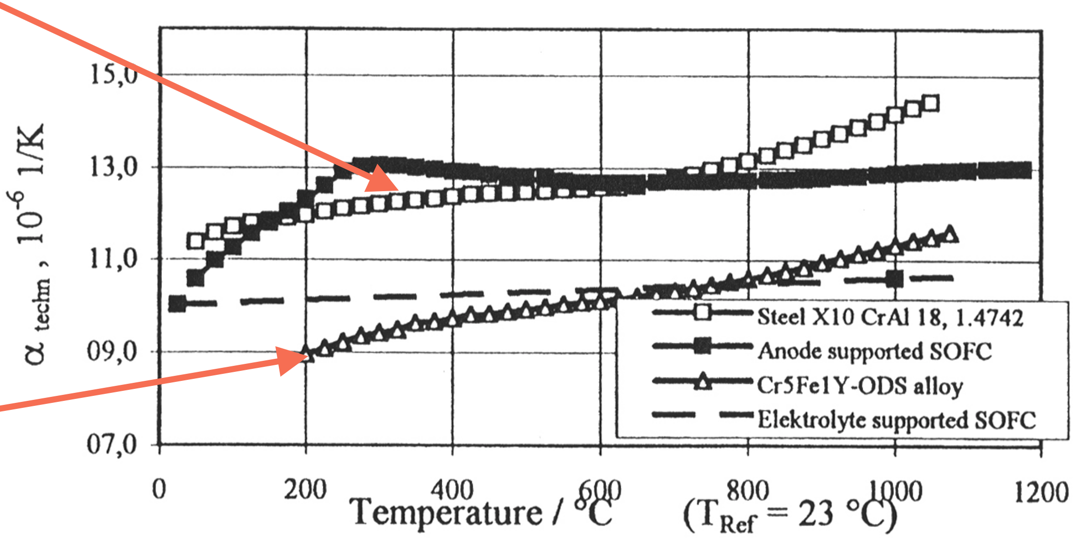
	Base Technology	Advances	Potential Benefit
Material	Ca-doped $LaCrO_3$ ceramic	Ferritic Stainless Steels	Increase in conductivity Lower Cost Increased Design Options TEC Matching with anode supported designs
Process	Molded Component	Metal Forming Processes	Lower Cost Increased Design Options

Coatings on the interconnect are also used to stabilize and lower contact resistance.

The combination of similar thermal expansion coefficient (TEC) with the anode supported unit cell and lower operating temperatures have created the potential for using lower cost ferritic stainless steel interconnect materials.

- **Metal Interconnects with anode-supported electrolytes**
  - Lower operating temperatures allow use of ferritic type stainless steels
    - e.g., Steel X10 CrAl 18 (18% Cr, 1% Al; KTN Germany)
    - lower cost materials
  - May need protective coating
- **Metal Interconnects with self-supporting (thick) electrolytes**
  - Plansee (Austria)–Cr5Fe1Y-ODS alloy
  - Similar TEC to cell structure
  - Issue–High cost of high chromium alloys

Thermal Expansion Behavior of Stack Materials

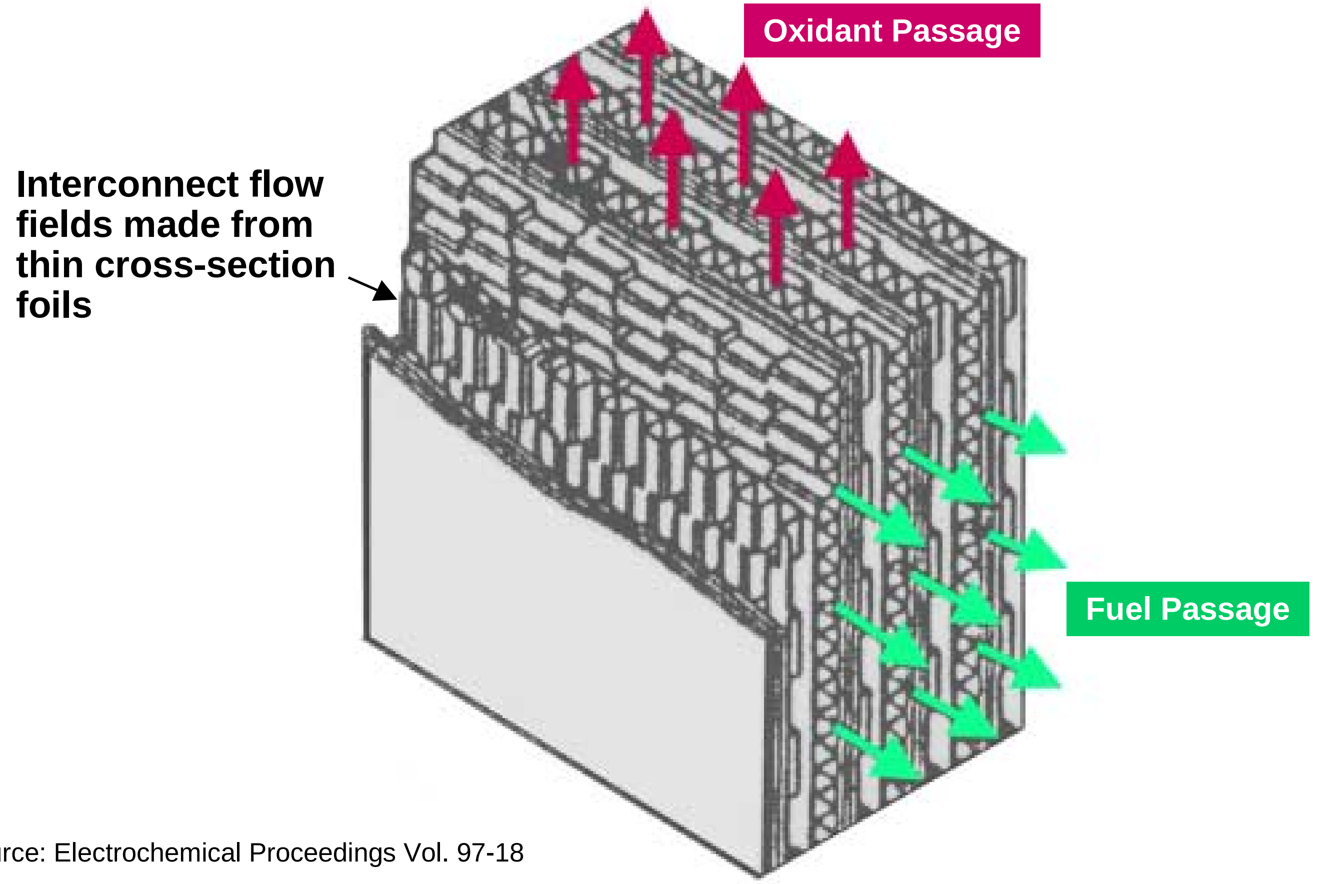


Source:H.P. Buchkremer, et. Al.,(Advances in the Anode Supported Planar SOFC Technology", Electrochemical Proceedings Volume 97-18 (Forschungszentrum Julich GmbH)

Developers stated that the combination of metallic ICs, thick nickel anode, and lower temperature have facilitated the development of more viable seal designs.

Metal interconnects may also allow one to design a compliant interconnect in addition to the TEC matching of materials.

Allied Signal Approach



Source: Electrochemical Proceedings Vol. 97-18

Outside of Japan, leading developers of planar designs with metallic ICs are Allied Signal, MSRI, Ceramatec, Global Thermo Electric/Julich, and Ceramic Fuel Cells Limited.

US	Europe	Japan	Other
• Allied Signal • University of Utah (MSRI*) (GRI, EPRI, NIST) • Ceramatec (SOFCo) (LBL, EPRI) • ZTEK	• Forschungszentrum Julich GmbH • Sulzer Hexis LTD. • DB/Dornier GmbH (??) (AEG) • Siemens AG (Westinghouse)	• Chubu Electric Power Company (Mitsubishi Heavy Industries, MHI) • Tokyo Gas Co • Osaka Gas Co (Murata Mfg. Co.) • Mitsui Engineering & Shipbuilding Co • Other	• Ceramic Fuel Cells Limited (CFCL) (Australia) • Global Thermoelectric Inc. (GTI) (Canada, “license” of Julich technology)

* Materials and Systems Research Inc.

Limited performance data is available in the open literature with which to calibrate the status of development. Discussions with developers indicate that power densities ≥ 500 mW/cm² are achievable in stacks and that viable seal designs are now possible.

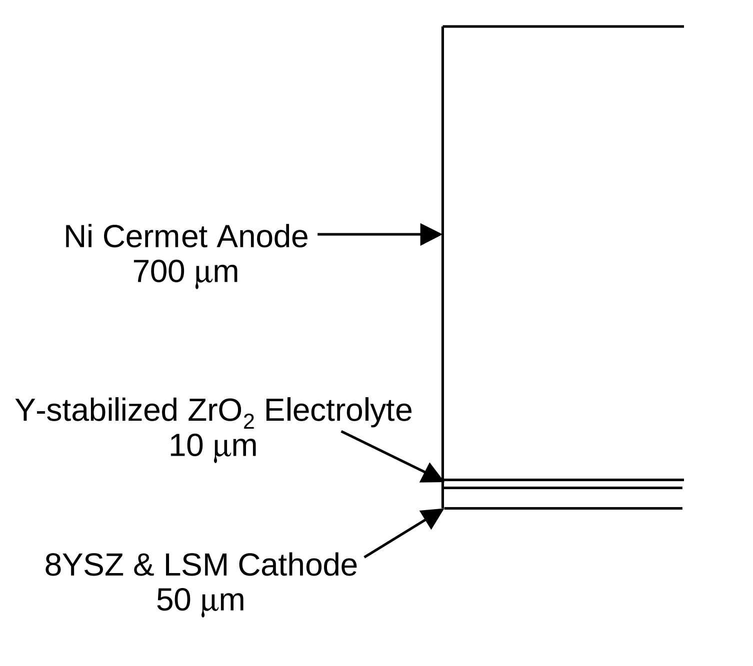
		Allied Signal	Utah (MSRI)	Ceramatec	Sulzer**	GTI Julich	CFCL
Temperature (°C)		800	800	800	920	750	750
Power Density (for H_2 fuel)	**mW/cm^2**	540*	1,800	143	200	220	>750
	mA/cm^2	1,200	4,000	220	130	320	?
Electrode Area (cm^2)		100		25	100	80	25
Cells in Stack		5	Unit Cell	4	5	5	Unit Cell
Design Electrolyte (µm)		5–10	10	4–10		5–50	20

*540 mW/cm^2 in stack
**CH_4 reformate fuel

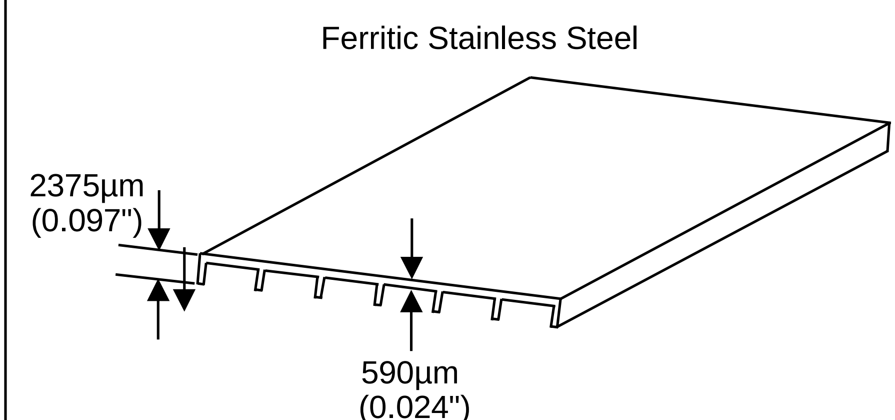
Hydrogen utilization data was not provided in the above references.

The anode supports the electrolyte and cathode layers. The Ni cermet (NiO) layer is reduced to form a porous nickel electrode.

Anode/Electrolyte/Cathode



One-Half Interconnect Layer

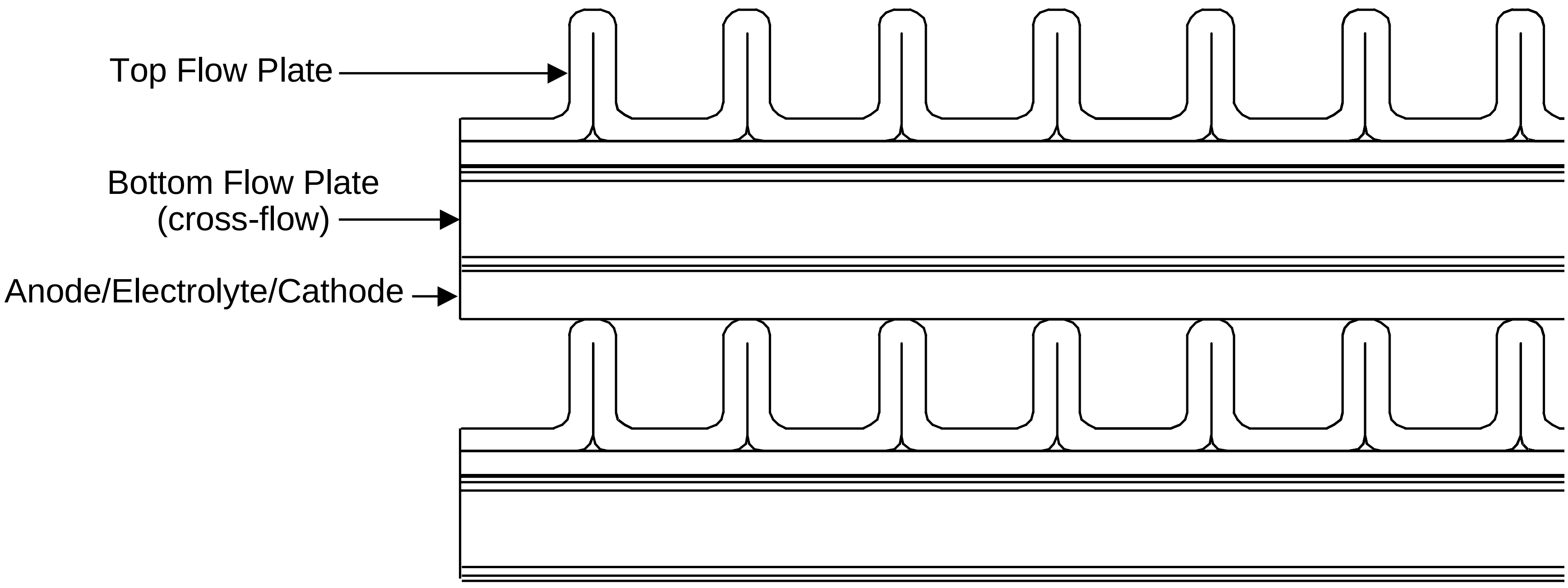


The anode/electrolyte/cathode layers represent a small (<1 mm) portion of total unit cell thickness.

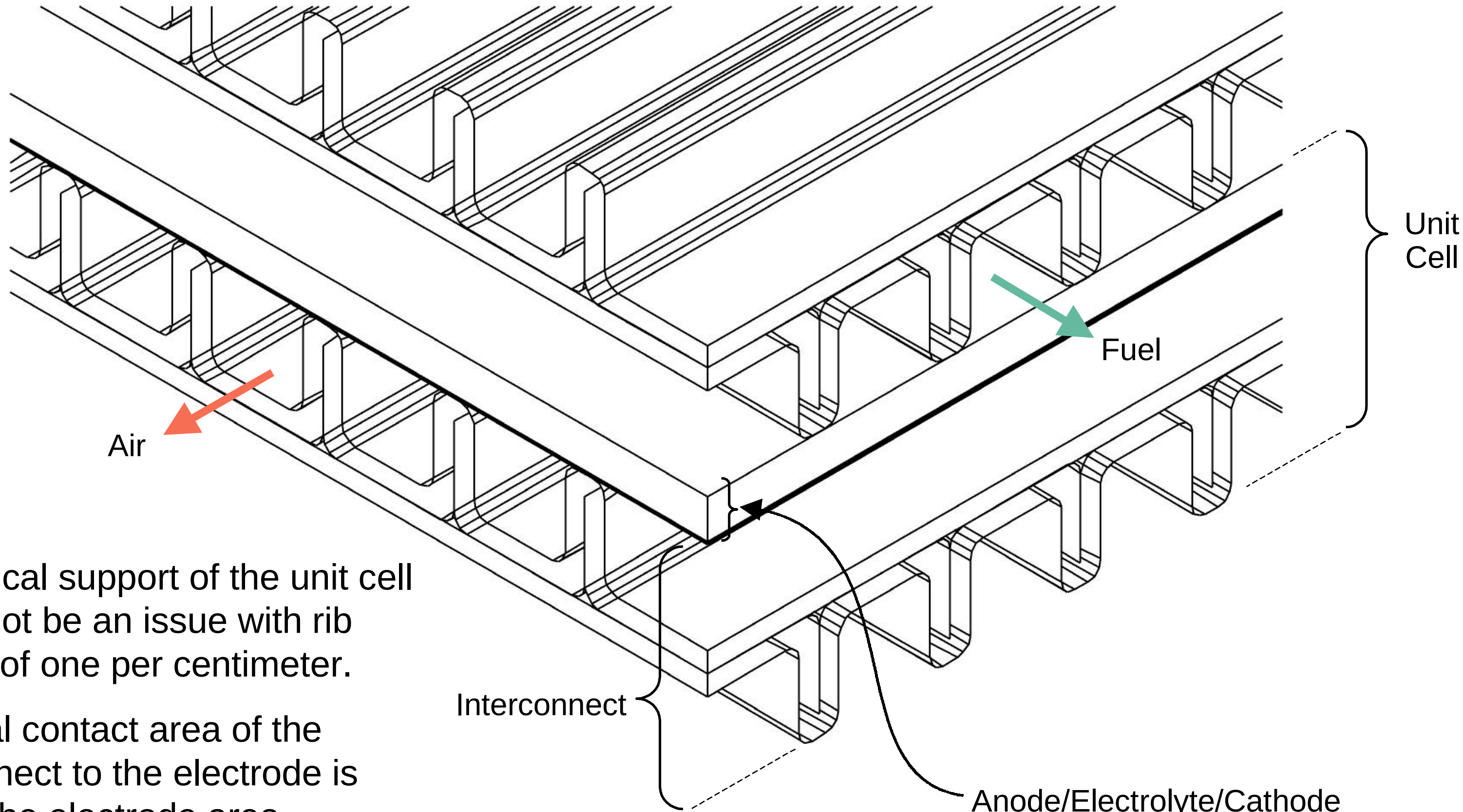
We selected a generic electrode-supported design based on traditional electrode materials and a roll-formed metal interconnect.

	Material	Thickness (μm)	Weight/Area (g/cm^2)	Envelope Volume/Area (cm^3/cm^2)
Anode	Ni Cermet	700	0.33	0.070
Electrolyte	Yttria Stabilized Zirconia (8% Y)	10	0.01	0.001
Cathode	Lanthanum Strontium Manganite	50	0.02	0.005
Interconnect (bipolar cross-flow)	Ferritic SS w/o coating	4320	1.29	0.432
	Total ▶	5080	1.65	0.51

The interconnect and electrochemical layers combine to produce a pitch of 5 unit cells per inch.



The bipolar interconnect is assumed to be two pieces that are manually stacked in cross-flow and bonded, and will be the thickest part of each cell.



- Mechanical support of the unit cell should not be an issue with rib spacing of one per centimeter.
- Electrical contact area of the interconnect to the electrode is 13% of the electrode area.

An active area of 100 cm^2 has been selected for cost analysis.

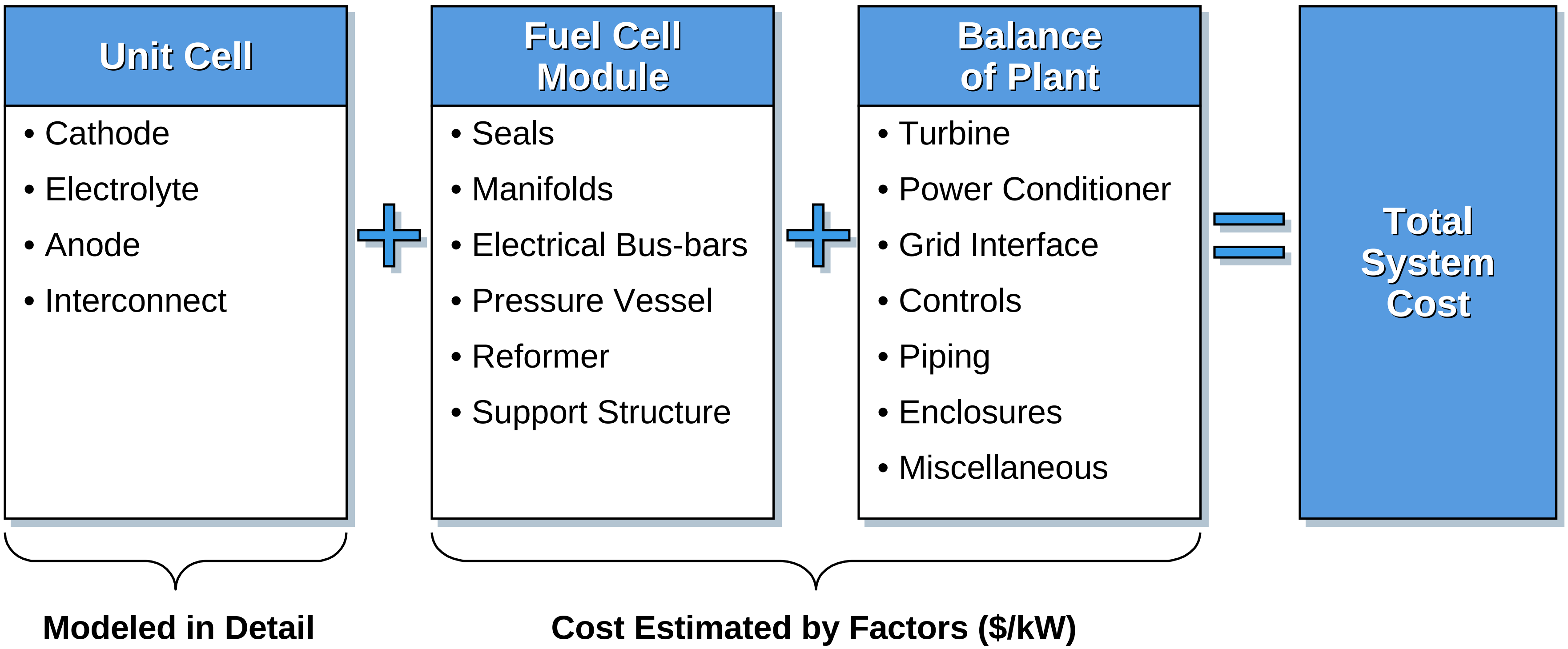
The generic electrode-supported design uses traditional electrode materials with a metal interconnect design.

		Anode Supported Electrolyte Metal Interconnect	**Electrolyte Supported Electrodes** (1997 METC Analysis) Ceramic Interconnect
Electrochemical Layers	**Anode (µm)**	700	37
	Electrolyte (µm)	10	165
	Cathode (µm)	50	28
	Wt./area (g/cm^2)	0.36	0.13
	Vol./area (cm^3/cm^2)	0.08	0.02
Interconnect	**Interconnect (µm)**	4320	4850
	Wt./area (g/cm^2)	1.29	0.94
	Vol./area (cm^3/cm^2)	0.43	0.49
Total Unit Cell	**Wt./area (g/cm^2)**	1.65	0.94
	Vol./area (cm^3/cm^2)	0.51	0.51
	Pitch (cells per inch)	5	5
	Density (g/cm^3)	3.2	1.8

Power density claims, critical to any projection of $/kW, vary over a wide range.

- Claims: $\geq$ 500 mW/cm^2
  - Even higher numbers from Utah MSRI, i.e. 1,800 mW/cm^2 for laboratory unit cells
- Issues:
  - Short-term unit cell results versus sustained stack performance
    - performance degradation over 40,000 hours
  - Fuel
    - pure H_2 vs. Reformate
      - internal on-electrode or thermally integrated reforming
  - Efficiency and fuel utilization data generally not provided
  - Temperature of operation also varies, e.g., from 650–900°C.

We have modeled the unit cell materials and processes in detail.



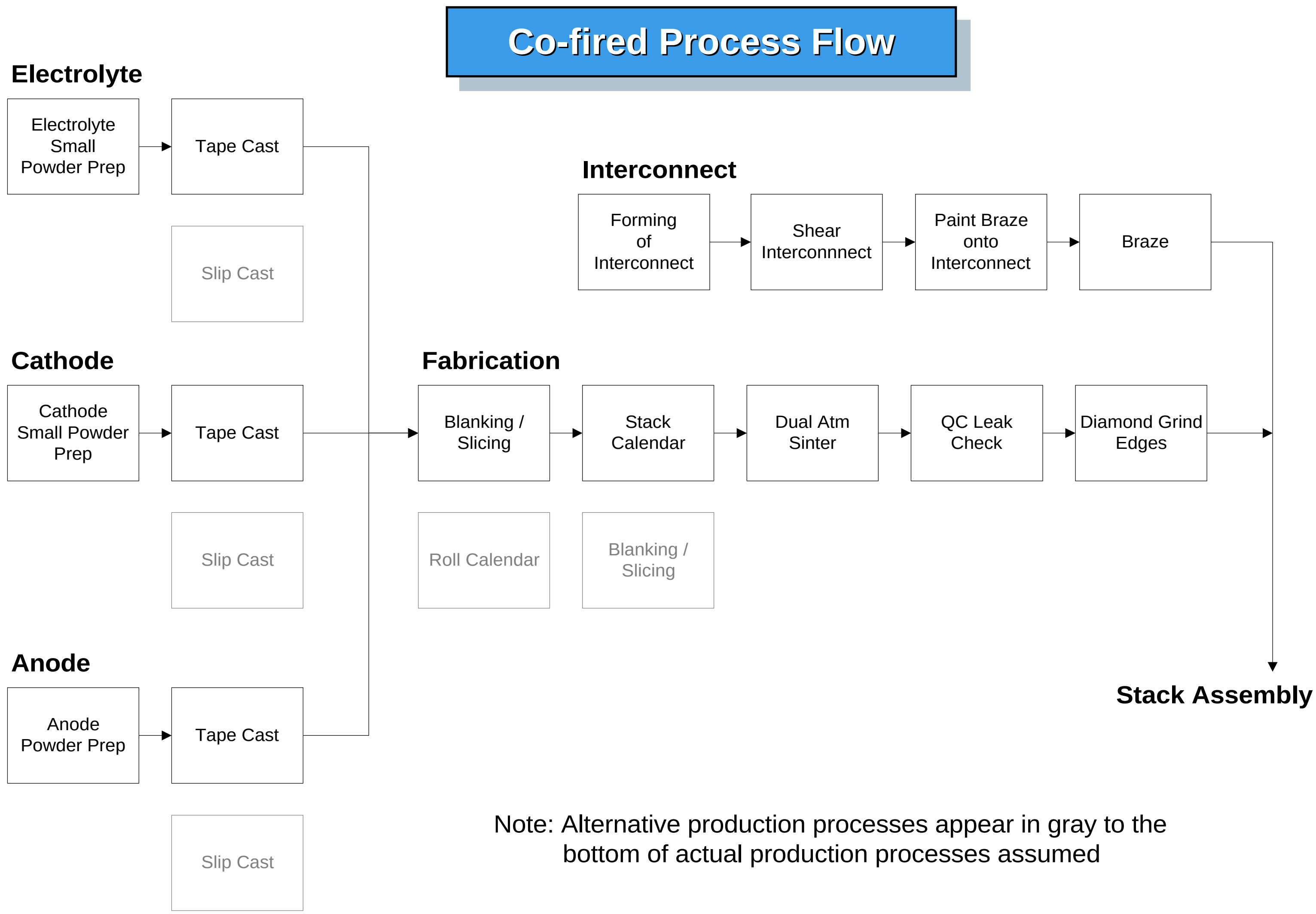
For the balance of stack components and balance of plant we have used estimates from earlier studies.

We evaluated two process flow approaches for the manufacture of the anode supported electrolyte design with metal interconnects.

Co-fired Process Flow	Multi-fired Process Flow
• Individually tape-cast layers • Laminated together • Co-fired in one step	• Tape-cast anode layer • Electrolyte and cathode layers applied by coatings • Sequential firing steps

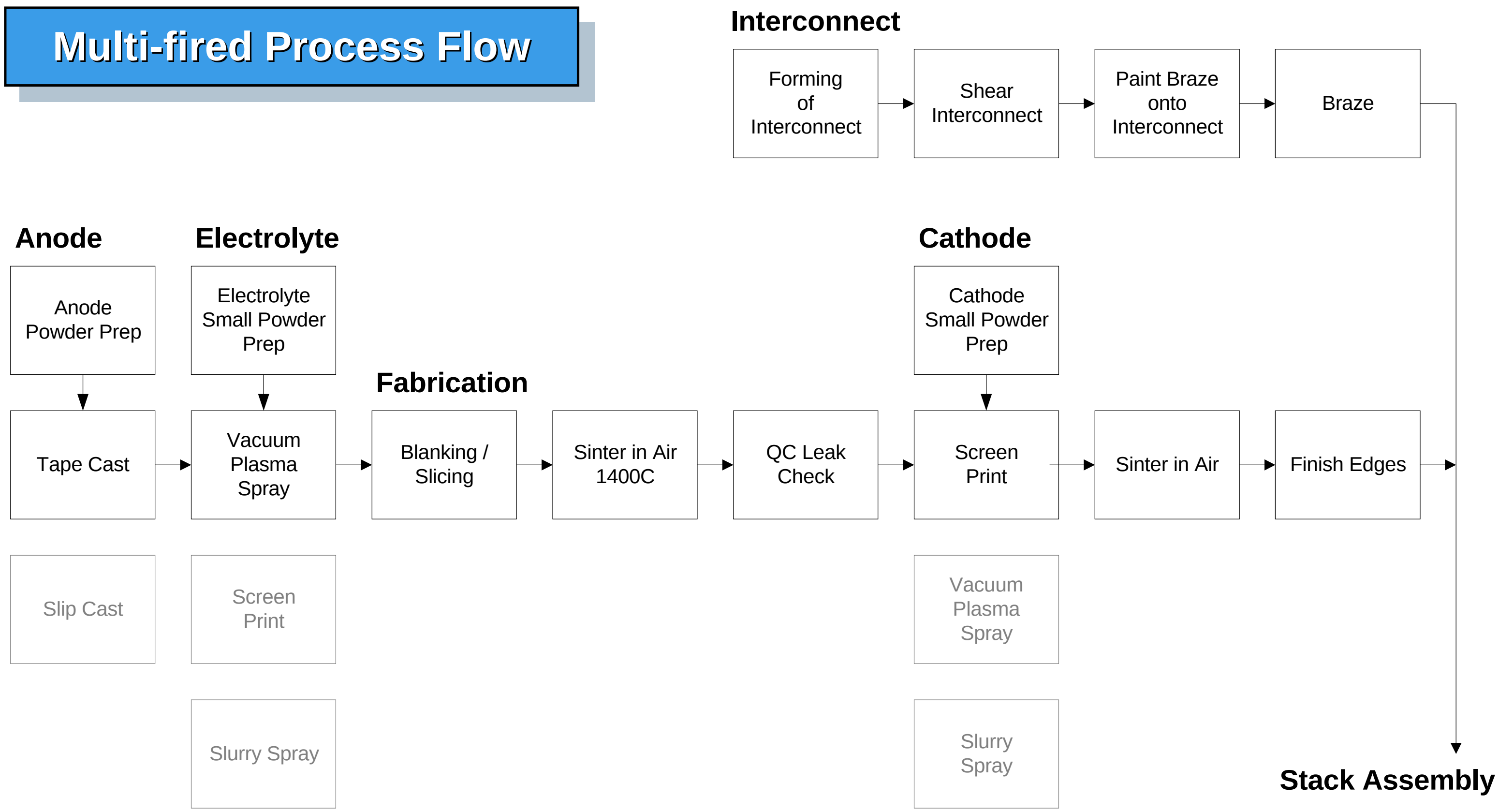
Other process options also exist such as slip casting or slurry coating.

In the first, all three electrical layers are tape cast and co-fired together.



Note: Alternative production processes appear in gray to the bottom of actual production processes assumed

In the second process, the electrical layers are fired twice. The anode is tape cast, the electrolyte is vacuum plasma sprayed on and fired together. The cathode is screen printed onto the electrolyte and the layers are fired again.



Note: Alternative production processes appear in gray to the bottom of actual production processes assumed

Baseline process flow assumptions include:

- Electrical layer (anode, cathode, and electrolyte) powders are made with ceramic processing steps of ball milling and calcining.
- Interconnects are made by metal forming techniques and blanking two pieces. These are then joined by applying a brazing paint and then brazing both pieces.
- Automated inspection of the electrical layers occurs after sintering, and includes checks for helium leaks, dimensions, flatness, and thickness.
- Design shown on page 33.
- Production volume: 250 MW per year.

Process Assumptions

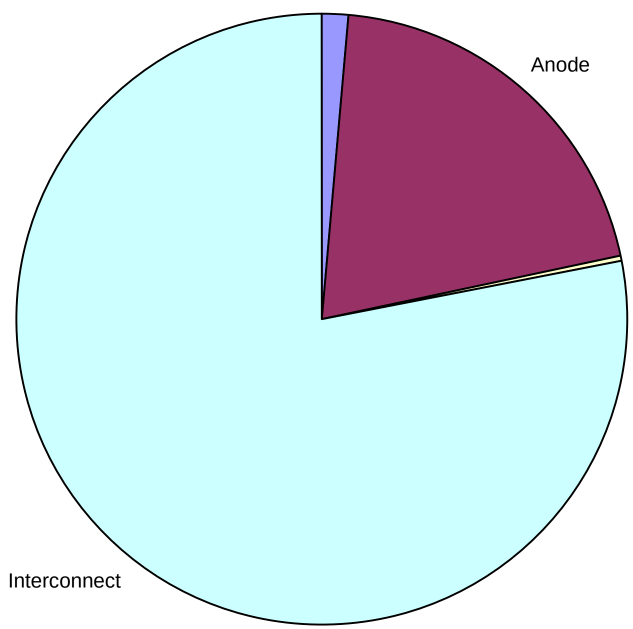
Process Description	Equipment Description	Equipment Cost	Cycle Time (mins)	Reject & Scrap (%)	Number Laborers per Station	Tool Cost ($)
Automated Tape Casting	Tape caster	$300,000	0.0004	0.0%	0.2	
Tile QC Vacuum Leak Test	Inspection Machine	$300,000	0.17	20.0%	1	
Vacuum Plasma Spray	Vacuum plasma gun	$1,200,000	1.00	2.0%	0.25	
Screen Print	Manual station	$20,000	0.02	1.0%	1	$100
Diamond Grind Stack Edges	Blanchard grinder	$300,000	30.00	5.0%	1	$2,000
IC Forming Step	Metal Forming	$130,000	0.00	3.0%	1	$12,100
IC Shear	Shear + flying die	$55,000	0.01	2.0%	1	$15,000
IC joining -- paint	Paint gun	$10,000	0.10	0.0%	0.2	
IC joining -- heat treat	Brazing furnace	$400,000	180.00	5.0%	0.2	
Stack Calendar	Press + heated dies	$20,000	0.50	1.0%	1	$15,000
Roll Calendar	Roll Calendar	$60,000	0.04	1.0%	0.2	
Blanking / Slicing	Press + heated dies	$150,000	0.17	1.0%	1	$30,000
Continuous Sinter in Air 12 hrs	Sintering Furnace	$500,000	720.00	2.0%	0.2	
Weigh Powders	Weigh Scales	$5,000	30.00	0.0%	0.2	
Ball Milling	Ball Mills	$22,000	300.00	2.0%	0.2	
Calcine	Calciner	$90,000	720.00	15.0%	0.2	
Air Classification	Air Classifier	$100,000	1.00	5.0%	0.2	

Baseline Manufacturing Assumptions

Production Volume	250	MW/year
Designed Fuel Cell Output	25	kW
Size of Tile	100	cm^2
% Active Area per Tile	100%	
Power Density	500	mW/cm^2
Tile Pitch	5	Tiles/inch
Ceramic Furnace Packing Factor	5%	
Interconnect Brazing Packing Factor	80%	
Indirect Salary	35000	$/year
Direct Wages	14	$/hour
Benefits on Wage and Salary	35%	
Indirect:Direct Labor Ratio	1	
Working Days per Year	300	
Working Hours per Day	24	
Capital Recovery Rate	15%	
Working Capital Period	3	months
Price of Production Space	580	$\$/m^2$
Price of Electricity	$0.08	/kWh
Auxiliary Equipment Cost	80%	
Equipment Installation Cost	80%	
Maintenance Cost	4%	
Product Life	10	yrs
Tool Life	10	yrs
Equipment Recovery Period	10	yrs
Building Recovery Period	20	yrs

The metal interconnect dominates the unit cell weight, and is the least expensive component.

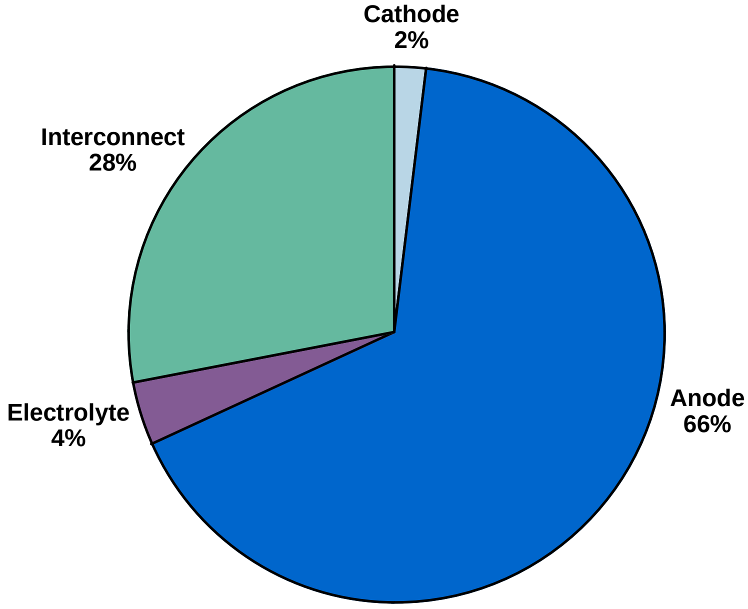
Metal IC Planar Unit Cell Weight



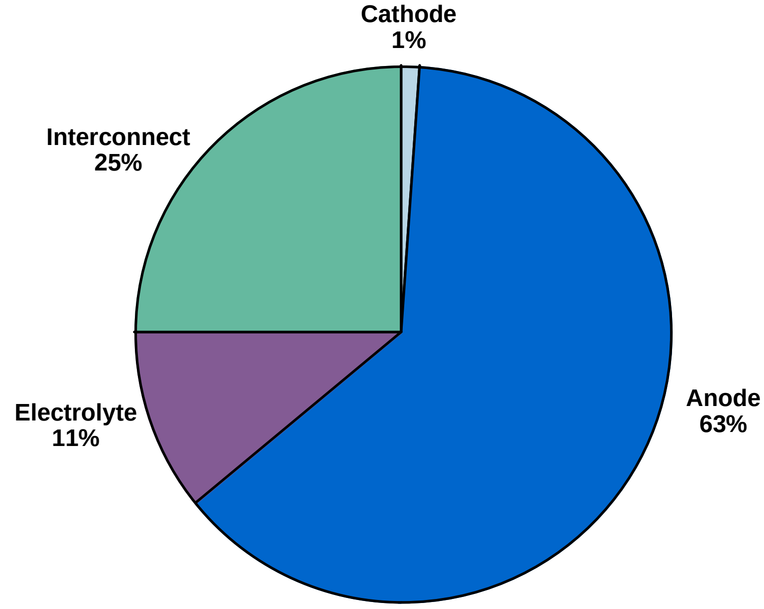
	%	Raw Material $/kg
Anode	20.2	$31
Cathode	1.4	$9
Electrolyte	0.4	$110
Interconnect	78.1	$3

The anode dominates material costs for both the co-fired and multi-fired process approaches.

Co-fired Metal IC Material Costs
$296/sq. meter



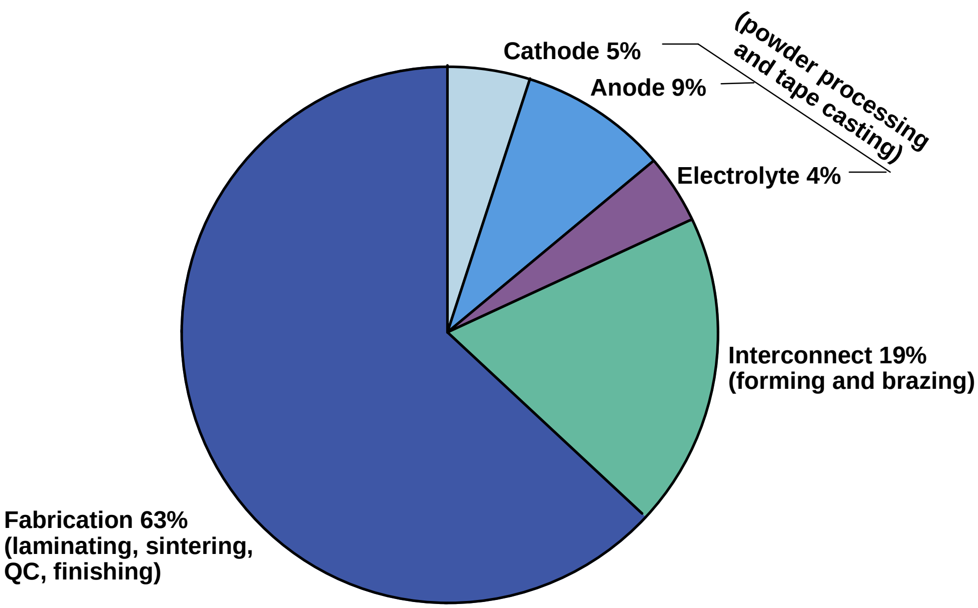
Multi-fired Metal IC Material Costs
$326/sq. meter



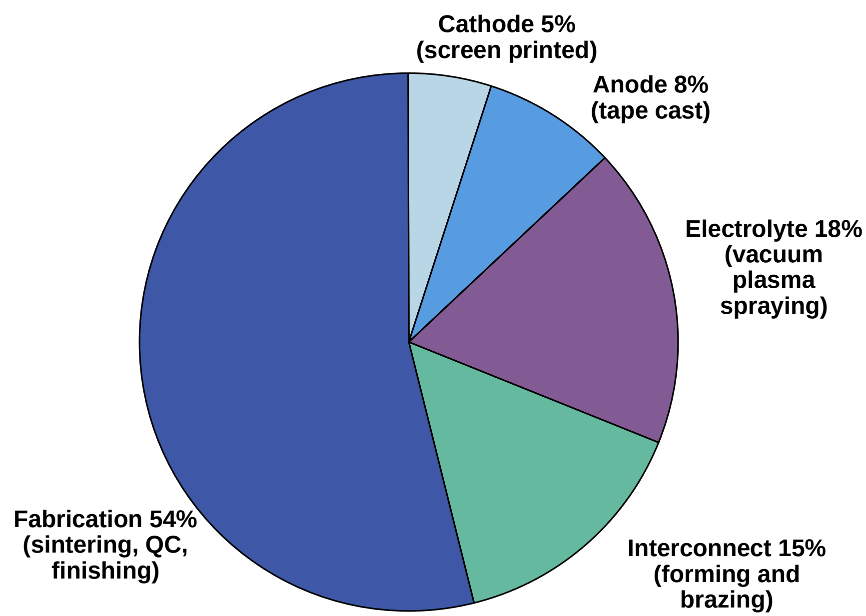
Electrolyte vacuum spray material losses are higher with the multi-layer process.

Fabrication dominates processing costs for both the co-fired and multi-fired process approaches.

Co-fired Metal IC Processing Costs
$82/sq. meter

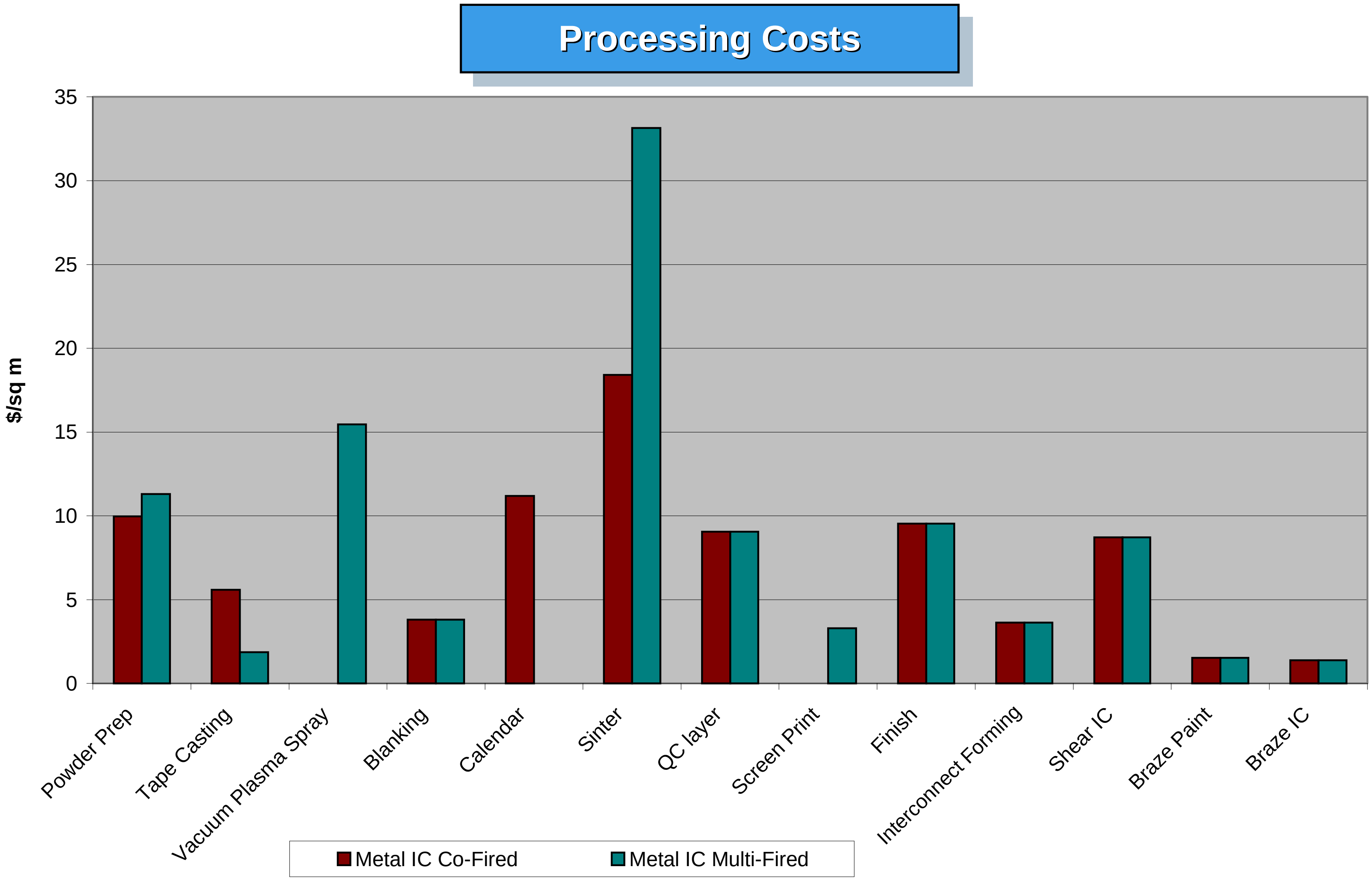


Multi-fired Metal IC Processing Costs
$103/sq. meter

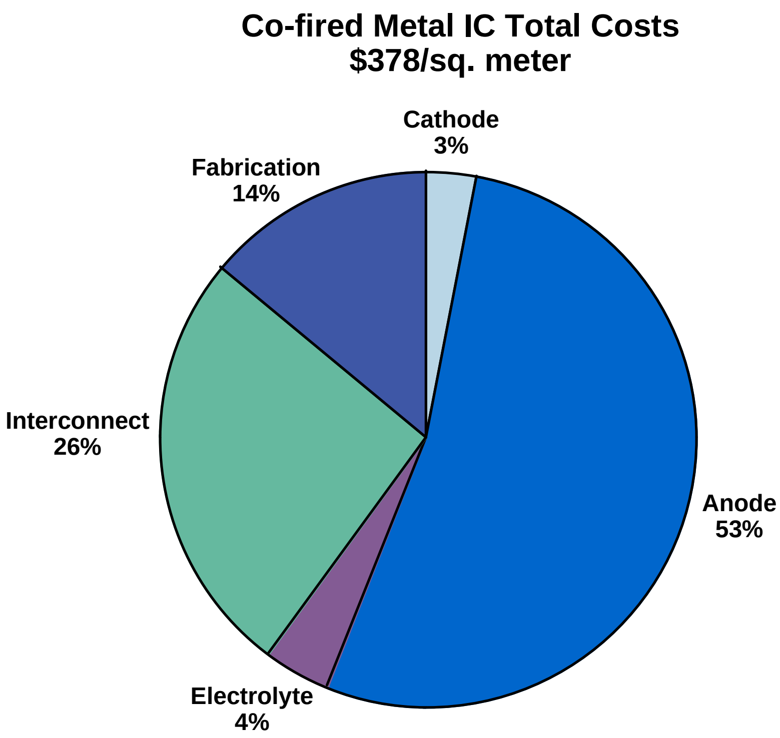


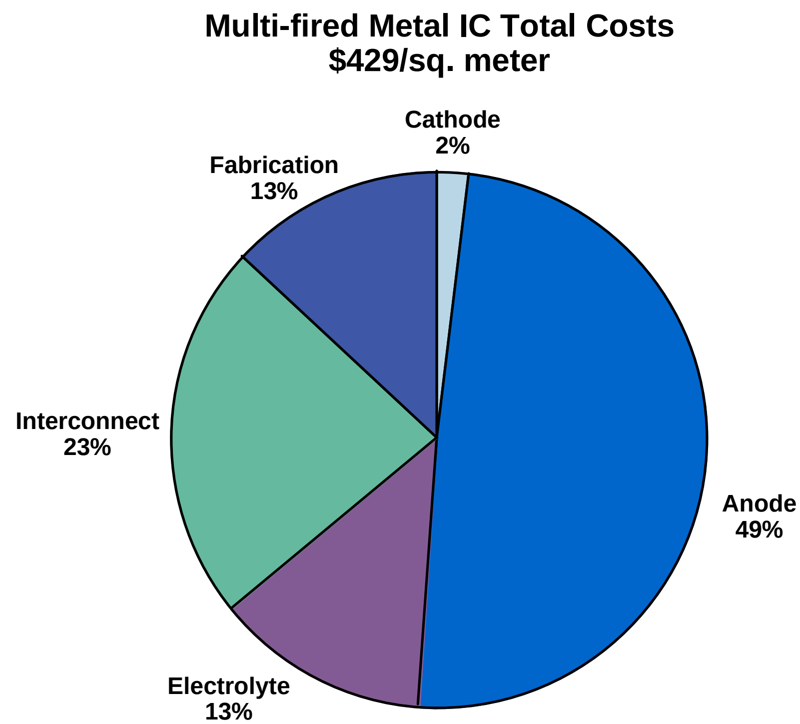
Electrolyte vacuum plasma spray and sintering costs are higher for the multi-fired process.

Sintering within the unit cell fabrication step is the largest factor in unit cell process costs.



The anode and interconnect layers dominate the total unit cell costs for both the co-fired and multi-fired processes.





The multi-firing process may be technically more attractive because sintering conditions can be tailored to the individual layers.

Baseline Assumptions: 5 cells/inch, 500 mW/cm^2, 250 MW/year

Multi-Fire

		$/kW	
		Mat	Process
Process Flow Steps	Anode	$40.83	$1.63
	Cathode	$0.90	$0.50
	Electrolyte	$7.14	$0.60
	Interconnect	$16.39	$3.42
	Layer Assy		$18.75
Sub-Total		$65.26	$24.91
Total		**$90.18**	

Co-Fire

		$/kW	
		Mat	Process
Process Flow Steps	Anode	$39.22	$2.51
	Cathode	$1.08	$1.49
	Electrolyte	$2.53	$1.23
	Interconnect	$16.39	$3.42
	Layer Assy		$12.11
Sub-Total		$59.22	$20.75
Total		**$79.97**	

However, at this stage of cost modeling, the two processes are similar in cost.

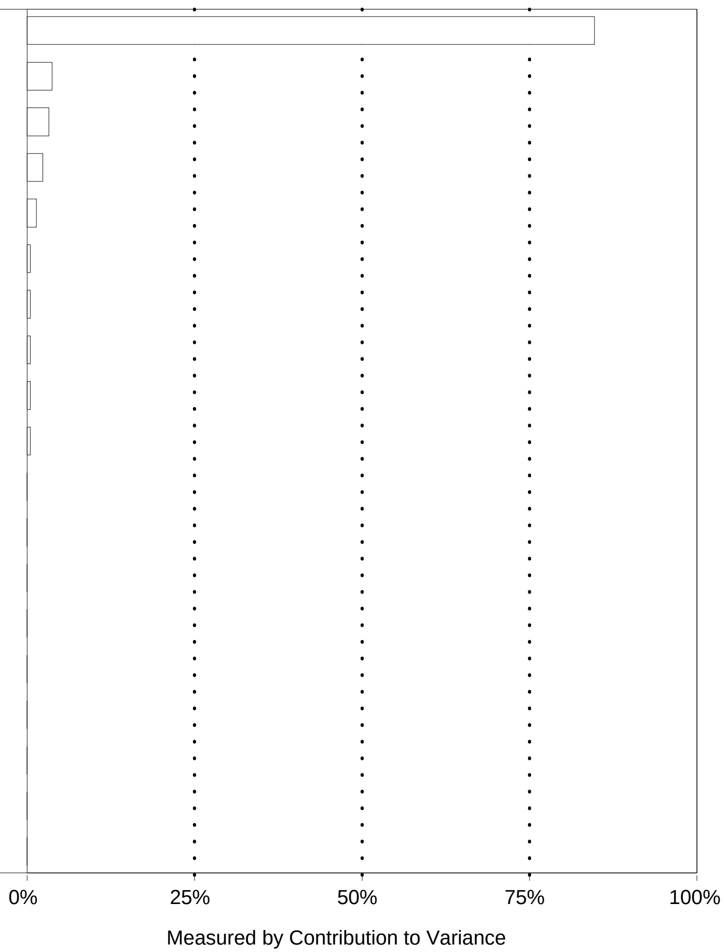
Triangular, normal, and uniform distributions of the most uncertain variables were chosen for evaluation using Monte Carlo analysis.

		Distribution	Min	Most Likely	Max	Units
General	**Pitch**	Triangular	2.5	5	10	Cells/inch
	Power Density	Triangular	300	500	700	mW/cm2
	Plant Output	Uniform	125		375	MW/year
	IC Rib Spacing	Triangular	0.5	1	2	Ribs/cm
	IC Stock Thickness	Uniform	17		23	mils
	% Active Area	Triangular	90%	90%	100%	%
Material	**Anode Density**	Triangular	4	4.76	5.5	g/cm3
	Cathode Density	Triangular	4	4.64	5.26	g/cm3
	Electrolyte Density	Normal		6		g/cm3
	TZ8Y - Yttria Cost	Normal		$110.00		$/kg
	Nickel Oxide Cost	Normal		$12.90		$/kg
	Nickel Cost	Normal		$18.00		$/kg
	Lanthanum Oxide Cost	Normal		$17.90		$/kg
	Stainless Steel Cost	Normal		$0.59		$/kg
Processing	**Brazing Furnace Electric Usage**	Uniform	60		120	kWH
	Ceramic Furnace Packing Factor	Triangular	3%	5%	10%	%
	Tile QC Rejection Rate	Triangular	10%	20%	30%	%
	Cathode Calcining Loss	Normal		15%		%
	Anode Calcining Loss	Normal		15%		%
	Electrolyte Calcining Loss	Normal		15%		%

The unit cell cost per kilowatt is most sensitive to power density.

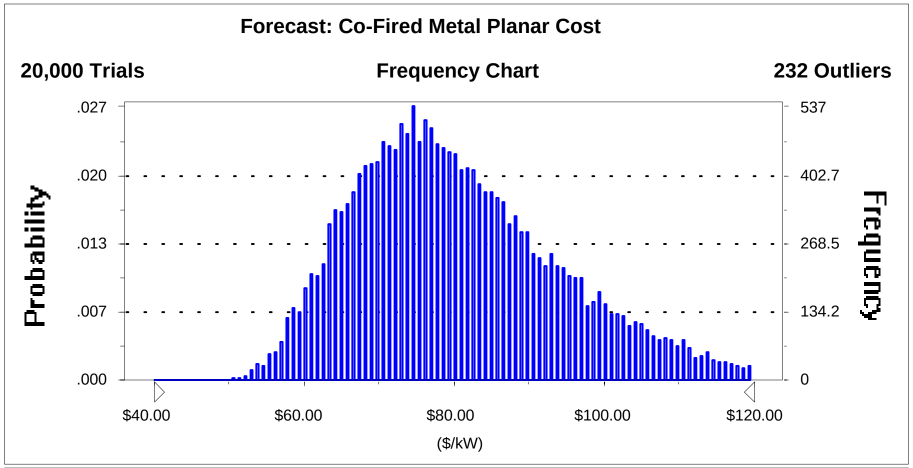
Sensitivity Chart — Target Forecast: Co-Fired Metal Planar Cost

Output per sq cm	84.6%
Tile QC Rejection Rate (%)	4.0%
Anode Density	3.6%
YSZ Electrolyte Cost $/g	2.3%
% Active Area per Tile	1.5%
Tile Pitch (Tiles/cm)	0.8%
Nickel 255 Cost ($/g)	0.8%
Production Volume	0.7%
Interconnect Matl. Gauge	0.7%
Desired Rib Spacing (cm)	0.5%
Anode Calcine Loss (%)	0.2%
Ceramic Furnace Packing Factor (% of ava	0.1%
Nickel Oxide Cost ($/g)	0.0%
Electrolyte Density	0.0%
Cathode Density	0.0%
Lanthanum Oxide Cost ($/g)	0.0%
Cathode Calcine Loss (%)	0.0%
SS430 Cost ($/g)	0.0%
Electrolyte Calcine Loss (%)	0.0%

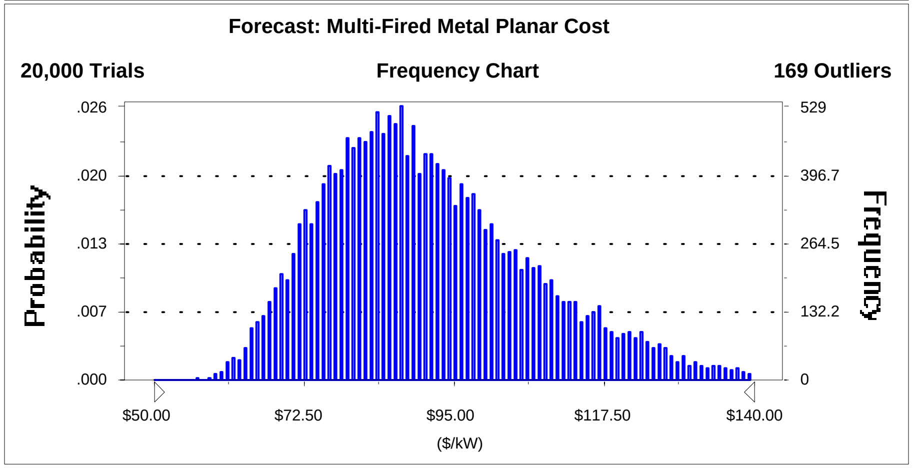


For current technology power densities, the unit cell cost of the Co-fired approach will be 48-154 $/kW. The unit cell cost of the Multi-fired approach will be 55-177 $/kW.

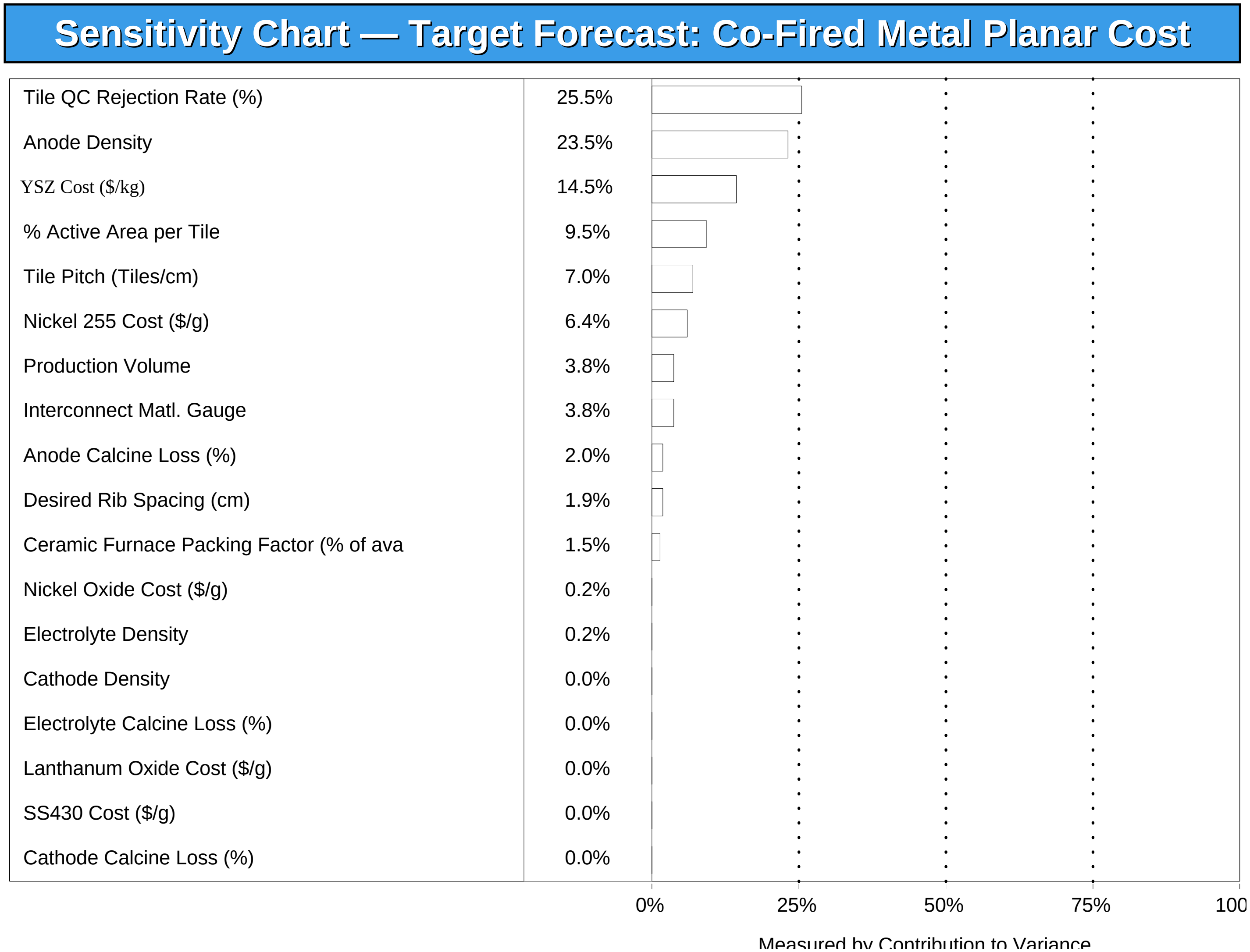
Forecast: Co-Fired Metal Planar Cost



Forecast: Multi-Fired Metal Planar Cost

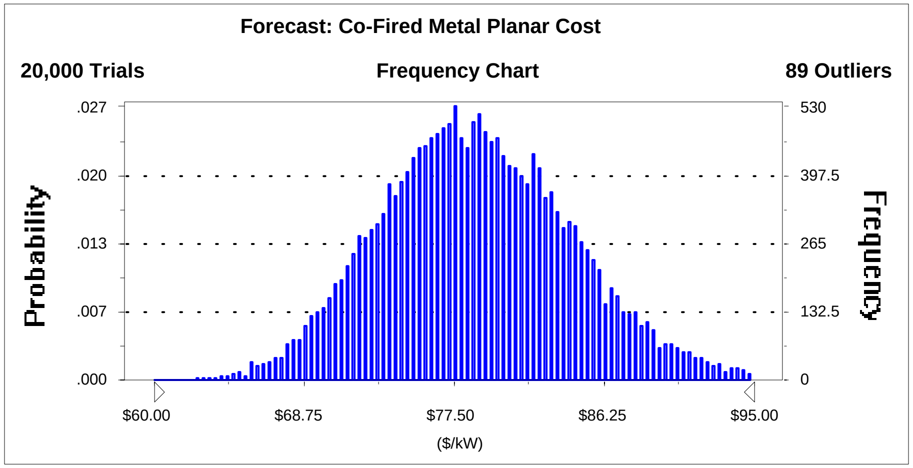


At constant 500 mW/cm^2 power density, unit cell cost per kilowatt are most sensitive to anode yields, density, and raw material.



For a projected power density of 500 mW/cm², the unit cell cost of the Co-fired approach will be 79 $/kW. The unit cell cost of the Multi-fired approach will be 89 $/kW (within one standard deviation).

Forecast: Co-Fired Metal Planar Cost



Forecast: Multi-Fired Metal Planar Cost